The Very Long Baseline Neutrino Oscillations Experiment

Presented to
FCP05 Neutrino Session

by
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Physics Case for the VLBNO Experiment

- ***<u>All parameters</u>*** **of neutrino oscillations can be measured in *<u>one</u>* experiment**
  - every one of the oscillation parameters is important to particle physics
  - the oscillation parameters contribute to important cosmology questions
  - a n_e ***appearance*** experiment is needed to determine all these parameters
  - a ***<u>broadband</u> Super Neutrino Beam*** at very long distances is key to success
  - the Very Long Baseline Neutrino Oscillation (***VLBNO***) Exp. is the best method

- **The massive VLBNO detector empowers *<u>additional forefront physics</u>***
  - a powerful next-generation ***Nucleon Decay*** search
  - supernova and relic neutrino searches
  - a deep underground detector in the prospective ***NSF DUSEL*** is ideal for VLBNO

- **The CP-violation parameter d_{CP} is the most difficult parameter to determine**
  - matter effects interact with CP-violation effects
  - the CP-violation phase d_{CP} has distinct effects over the ***<u>full 360º range</u>***
  - antineutrino running gives a complementary way to demonstrate CP-violation

- **The off-axis beam method requires multiple distances and detectors**
  - all experiments will require of order 10 Snomass years of running
  - multiple detectors/beams will require careful control of systematic errors

Questions About the VLBNO Experiment

Won't HyperK + 4MW J-PARC beam complete all the measurements?

- no, the 295km T2K baseline is too short for the solar term and matter effects
- the off-axis T2K neutrino beam requires at least one other big experiment to determine d_{CP} without ambiguities; systematic errors are a concern

Isn't VLBNO much more expensive than other approaches?

- the VLBNO cost is comparable to or lower than other less complete methods
- the VLBNO detector can be made in ~100kTonne steps, phased over time
- VLBNO plans to share the large Nucleon Decay Detector in NSF's ***DUSEL***

What about the background from p^0 inelastic events in VLBNO?

- sophisticated Monte Carlo simulations with state-of-the-art SuperK pattern recognition and maximum likelihood methods have mitigated this issue

Why not determine CP-violation with antineutrino running?

- antineutrino measurements will require of order 10 Snomass years of running
- each proposed detector needs to achieve good statistics for most parameters

Isn't the AGS at BNL needed for RHIC and RSVP?

- RHIC runs very compatibly with AGS and RSVP doesn't use all the available time (RSVP is planned for 25 weeks/yr for 5 years
- the neutrino oscillation/nucleon decay experiment could be active for decades

Electron Neutrino Appearance by Oscillation in Vacuum

The equation for oscillation[a] of n_m ® n_e neutrinos in vacuum is given by:

$$P(n_m \text{ ® } n_e) = \sin^2(q_{23}) \sin^2(2q_{13}) \sin^2(Dm^2_{31} L/4E_n) \qquad \text{'Term 1'}$$

$$+ \tfrac{1}{2} \sin(2q_{12}) \sin(2q_{13}) \sin(2q_{23}) \cos(q_{13}) \times$$
$$\sin(Dm^2_{21} L/2E_n) \times [\, \sin(d_{CP}) \sin^2(Dm^2_{31} L/4E_n)$$
$$+ \cos(d_{CP}) \sin(Dm^2_{31} L/4E_n) \cos(Dm^2_{31} L/4E_n) \,] \qquad \text{'Term 2'}$$

$$+ \sin^2(2q_{12}) \cos^2(q_{13}) \cos^2(q_{23}) \sin^2(Dm^2_{21} L/4E_n) \qquad \text{'Term 3'}$$

+ matter effects + smaller terms

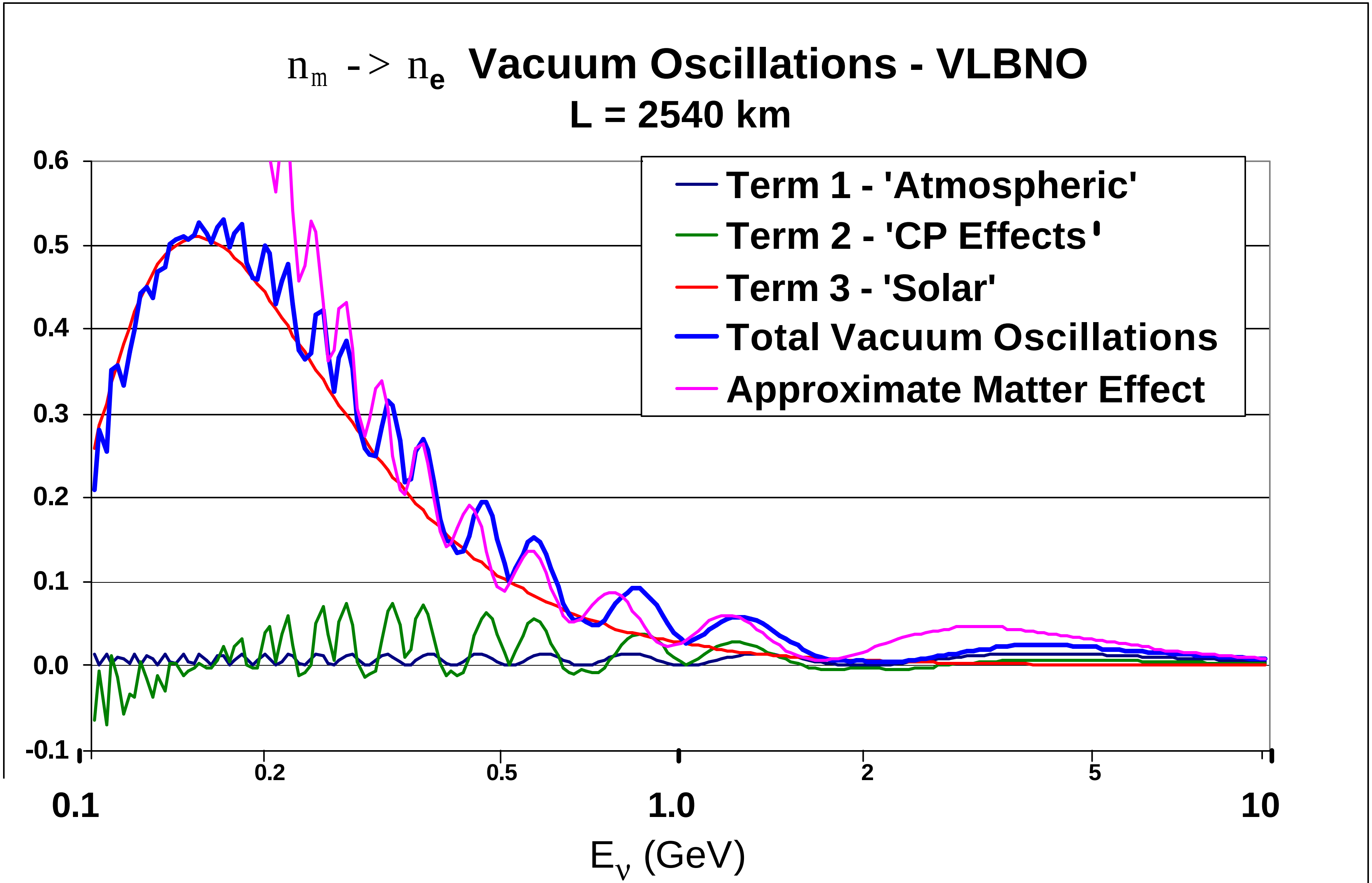
$$Dm^2_{31} \equiv m^2_3 - m^2_1 = Dm^2_{32} + Dm^2_{21} \sim Dm^2_{32}$$

What do we learn by contemplating this long algebraic expression?

- **simple inspection won't reveal all the experimental implications**
- **detailed calculations will clarify all the important experimental issues**
- **key *oscillation parameters* still to be measured are shown in red**
- **the VLBNO method exploits the known oscillation distance scales in green**

[a] W. Marciano, Nuclear Physics B (Proc. Suppl.) 138, (2005) 370-375

Electron Neutrino Appearance by Oscillation in Vacuum



Electron Neutrino Appearance With Matter Effects

The oscillation for $\nu_\mu \rightarrow \nu_e$, including the *matter effect*, is given approximately by[a]:

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23})\,\sin^2(2\theta_{13})\,\sin^2((A-1)\Delta)/(A-1)^2$$

$$+\ \alpha\ 8\ J_{CP}\,\sin(\Delta)\,\sin(A\Delta)\,\sin((1-A)\Delta)\,/\,(A\,(1-A))$$

$$+\ \alpha\ 8\ I_{CP}\,\cos(\Delta)\,\sin(A\Delta)\,\sin((1-A)\Delta)\,/\,(A(1-A))$$

$$+\ \alpha^2\cos^2(\theta_{23})\,\sin^2(2\theta_{12})\,\sin^2(A\Delta)\,/\,A^2$$

$$J_{CP} = \sin(\delta_{CP})\,\cos(\theta_{13})\,\sin(2\theta_{12})\,\sin(2\theta_{13})\,\sin(2\theta_{13})\,/\,8$$

$$I_{CP} = \cos(\delta_{CP})\,\cos(\theta_{13})\,\sin(2\theta_{12})\,\sin(2\theta_{13})\,\sin(2\theta_{13})\,/\,8$$

$$\alpha = \Delta m^2_{21}\ /\ \Delta m^2_{31}\ ;\ \ \Delta = \Delta m^2_{31}\,L/4E_\nu\ ;\ \ A = 2VE_\nu/\Delta m^2_{31}\ ;\ \ \Delta m^2_{31} \equiv m^2_3 - m^2_1$$

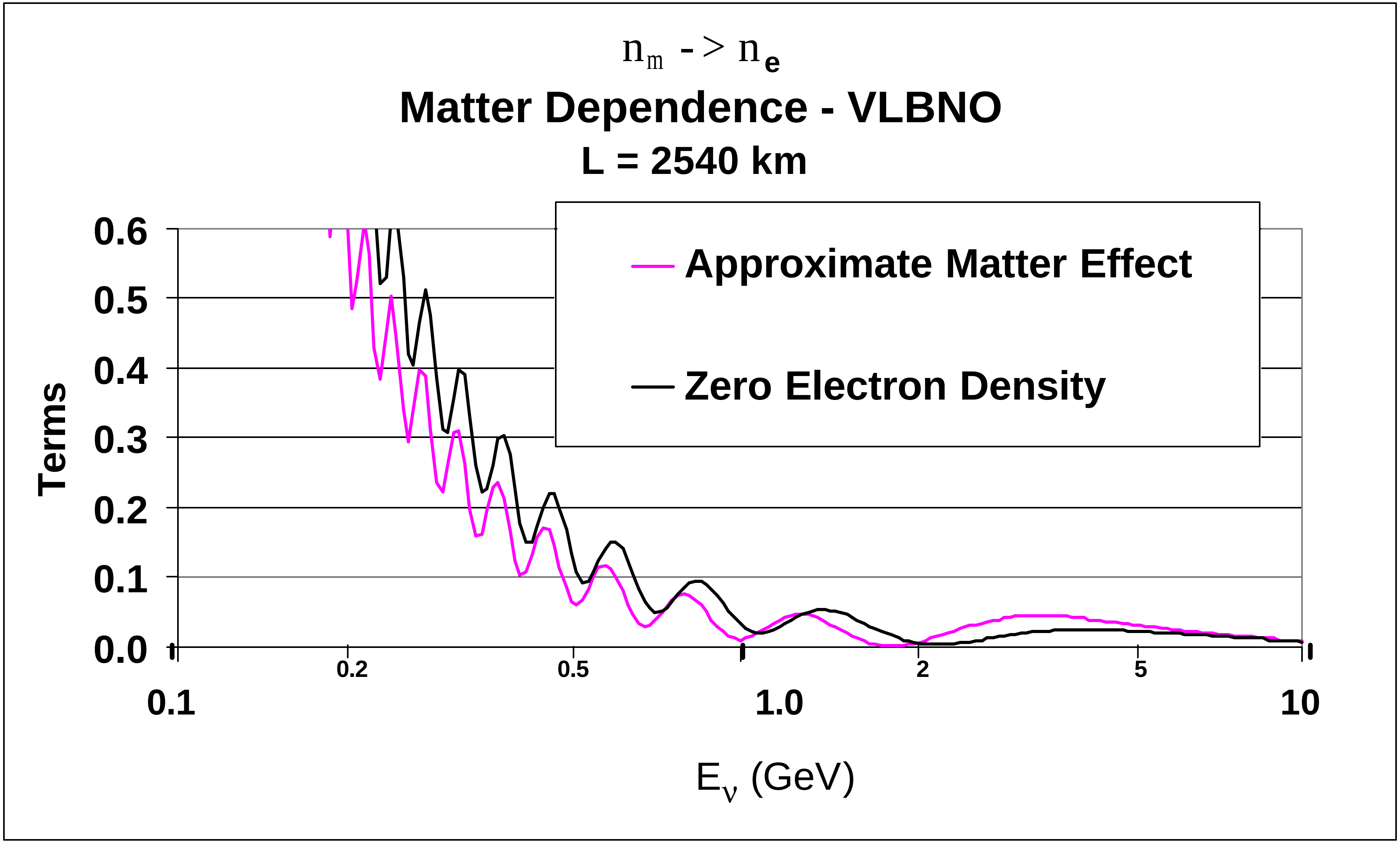
$V = \sqrt{2}G_F n_e$; n_e is density of electrons along the path

This expression separates terms by the the following:

- **the first term shows the effect of $\sin^2(2\theta_{13})$**
- **the second and third terms show the effects of CP symmetry**
- **the J_{CP} term changes sign when calculating anti-neutrinos,** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- matter effects come into all terms via the 'A' factors in blue

[a] Barger et al.,Phys. Rev. D63: 113011 (2001); Huber et al., Nucl. Phys. B645, 3 (2002); M. Freund, Phys. Rev. D64: 053003 (2001); Barger et al. Phys. Rev. D65: 073023 (2002)

Sensitivity to Matter Effect



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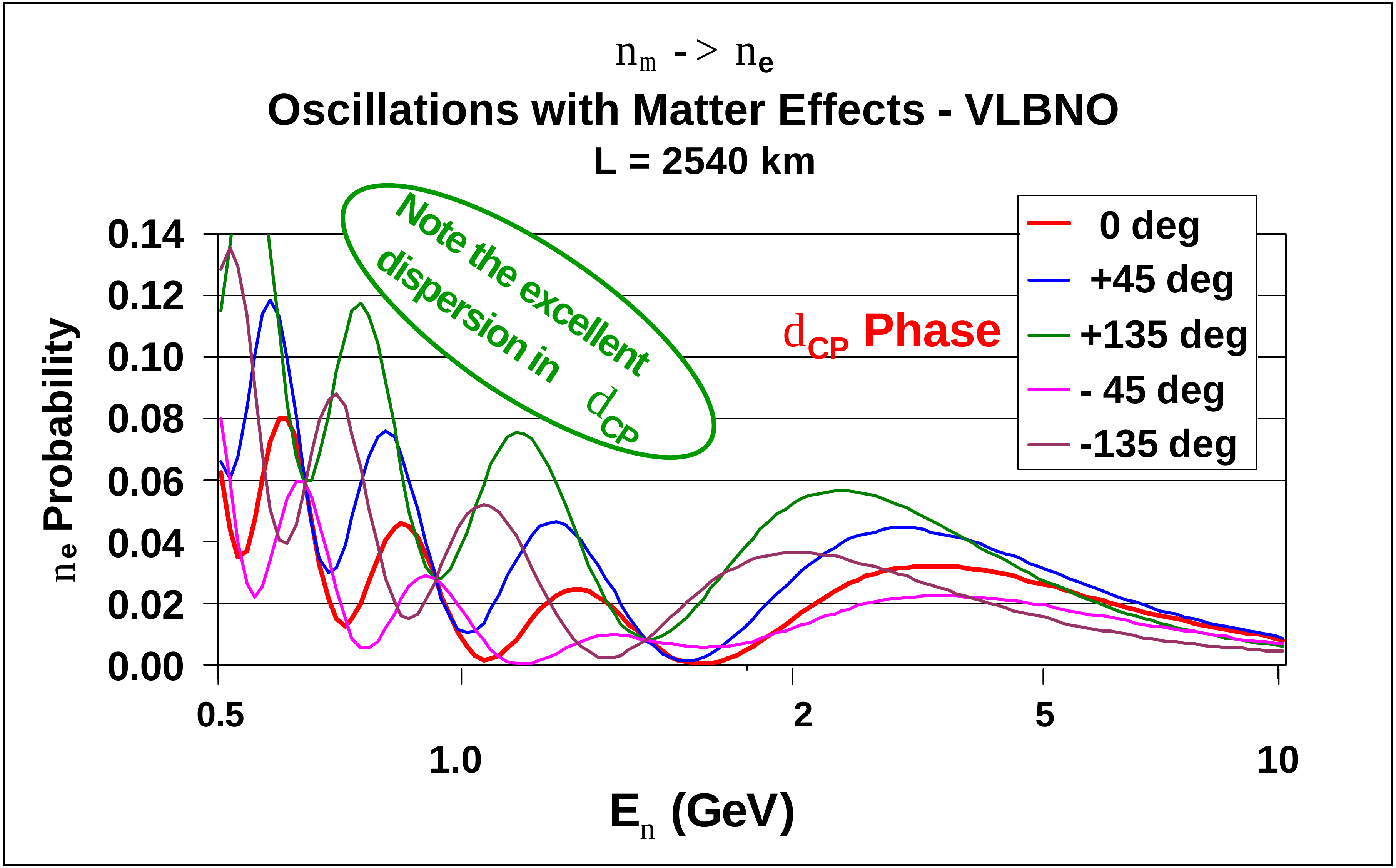
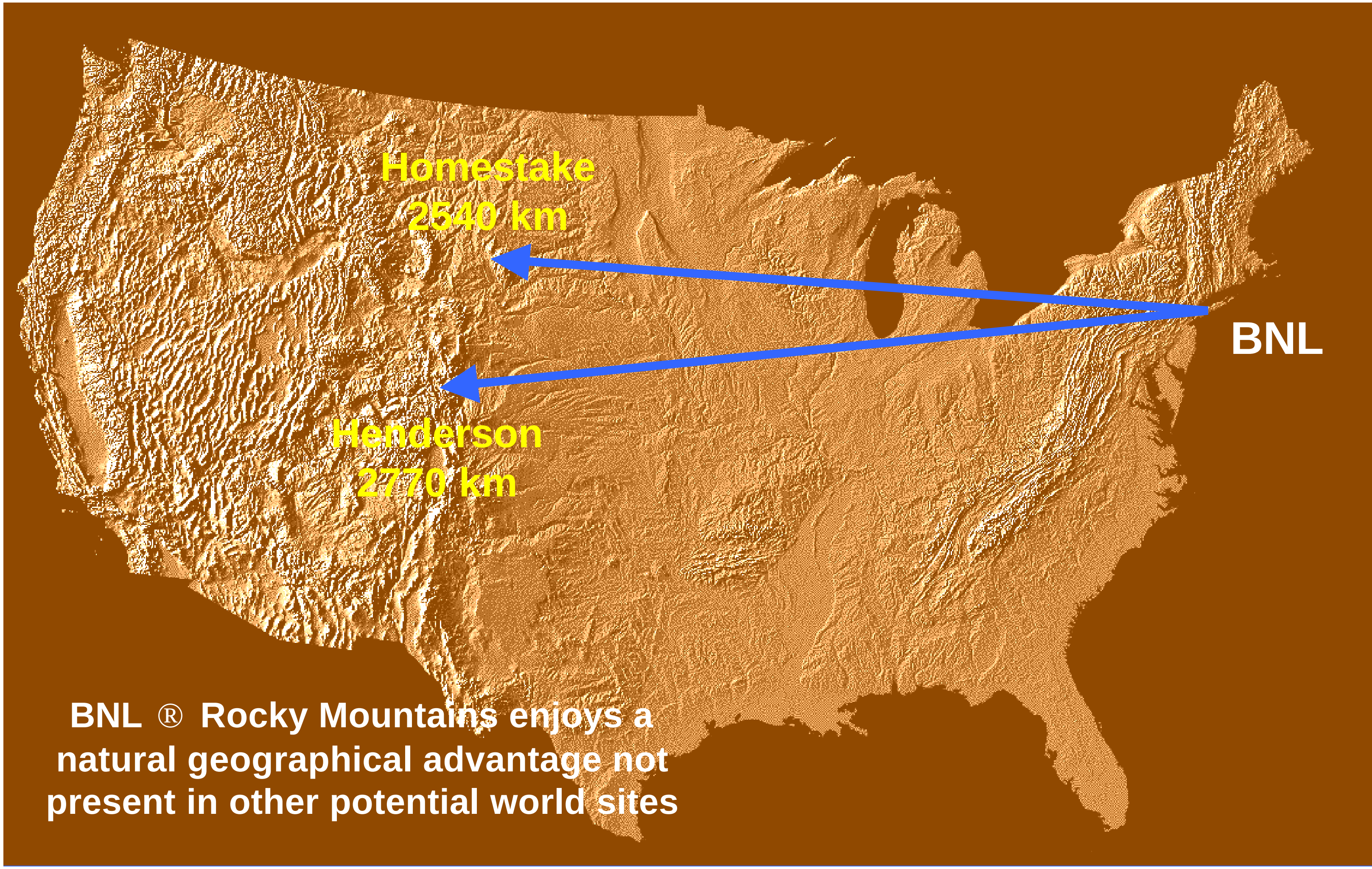
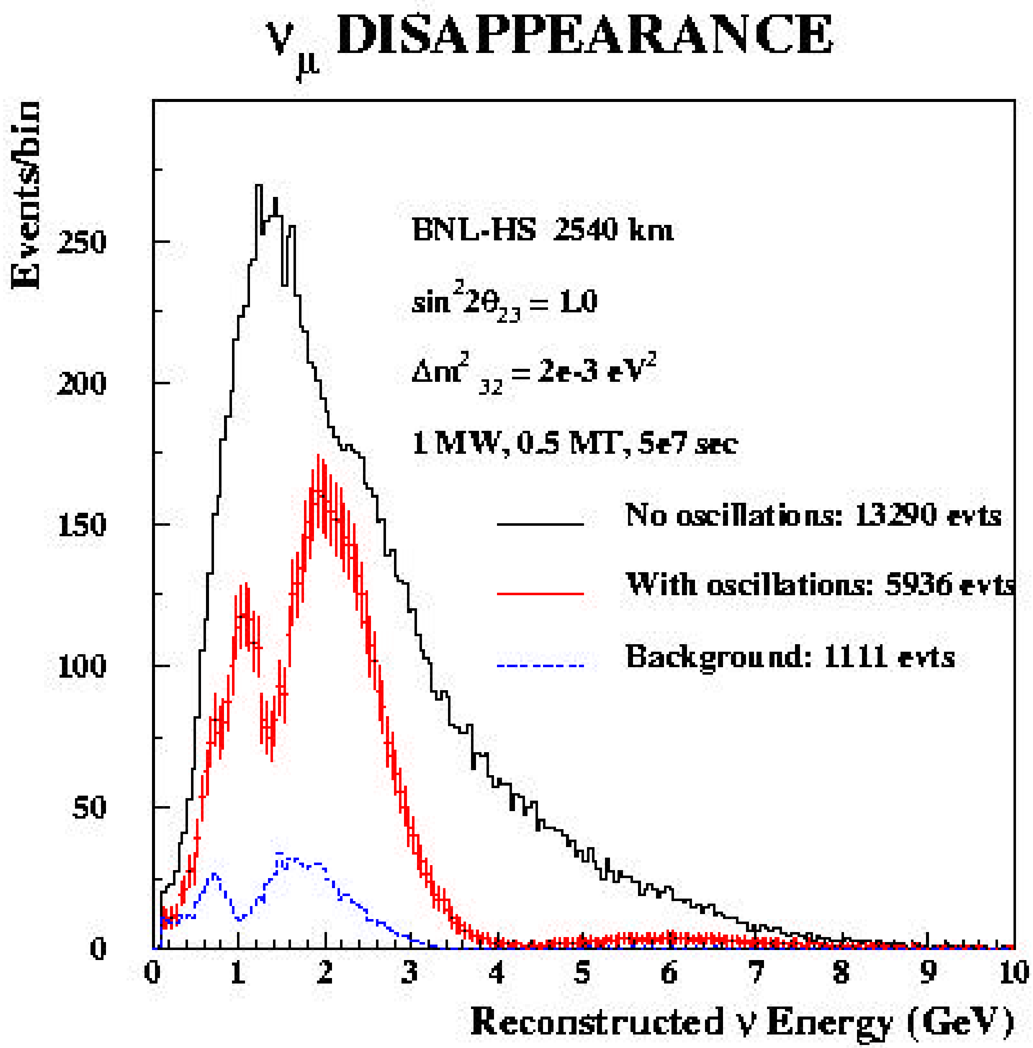
Electron Neutrino Appearance – CP Phase Sensitivity



BNL ® Rocky Mountains *Super Neutrino Beam*

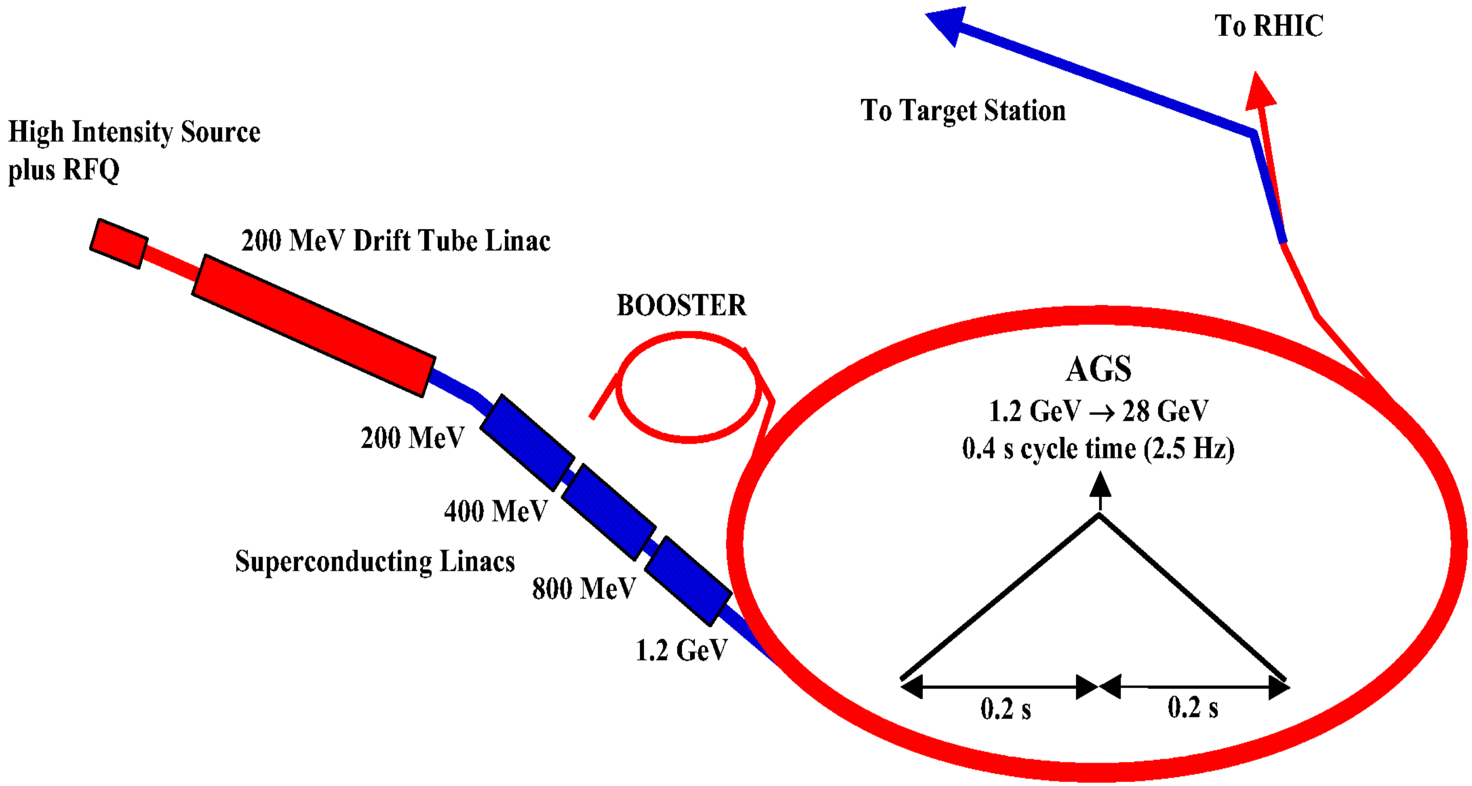


Very Long Baseline Neutrino Experiment



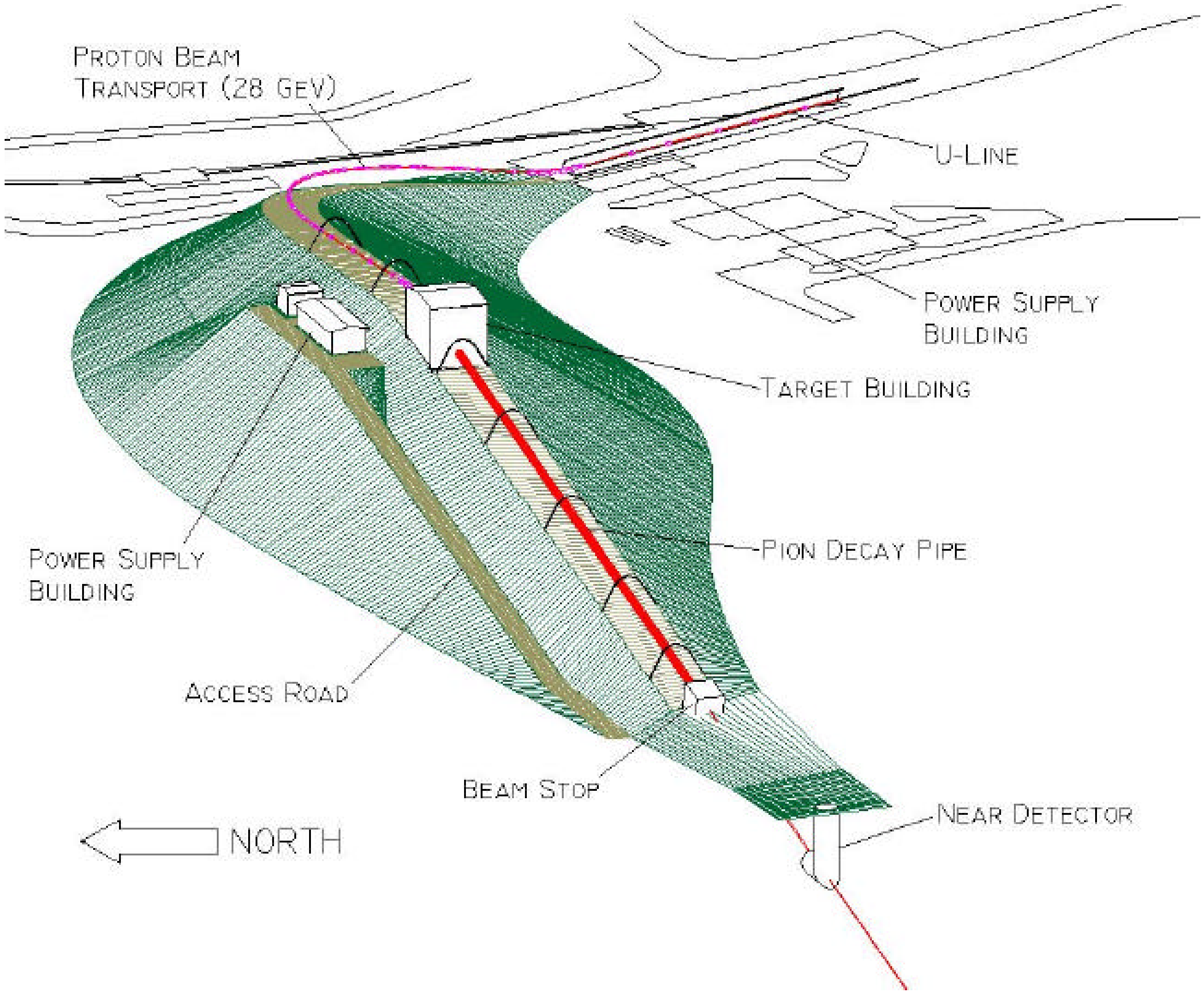
- neutrino oscillations result from the factor sin^2(Dm$_{32}^2$ L / 4E) modulating the n flux for each flavor (here n$_m$ disappearance)
- the oscillation period is directly proportional to distance and inversely proportional to energy
- with a *very long baseline* actual oscillations are seen in the data as a function of energy
- the multiple-node structure of the very long baseline allows the Dm$_{32}^2$ to be precisely measured by a *wavelength* rather than an amplitude (reducing systematic errors)

1-2 MW *Super Neutrino Beam* at AGS



- BNL completed October 8, 2004, a Conceptual Design to support a new proposal to DOE to upgrade the AGS to 1-2 MW target power and construct the wide-band ***Super Neutrino Beam*** as listed in the DOE's "Facilities for the Future of Science" plan of November 2003

3-D *Super Neutrino Beam* Perspective



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February 28, 2005

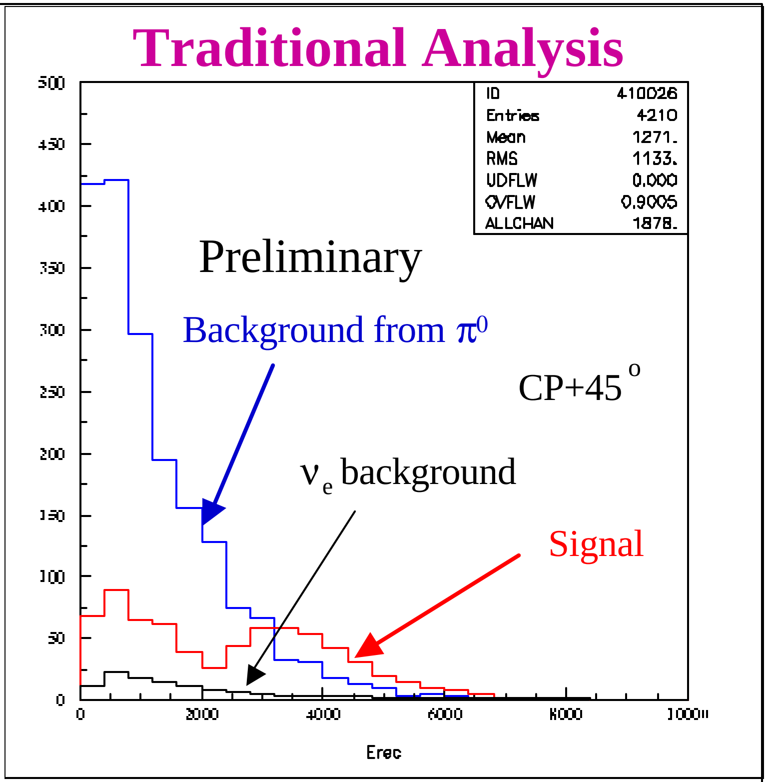
Signal/Background

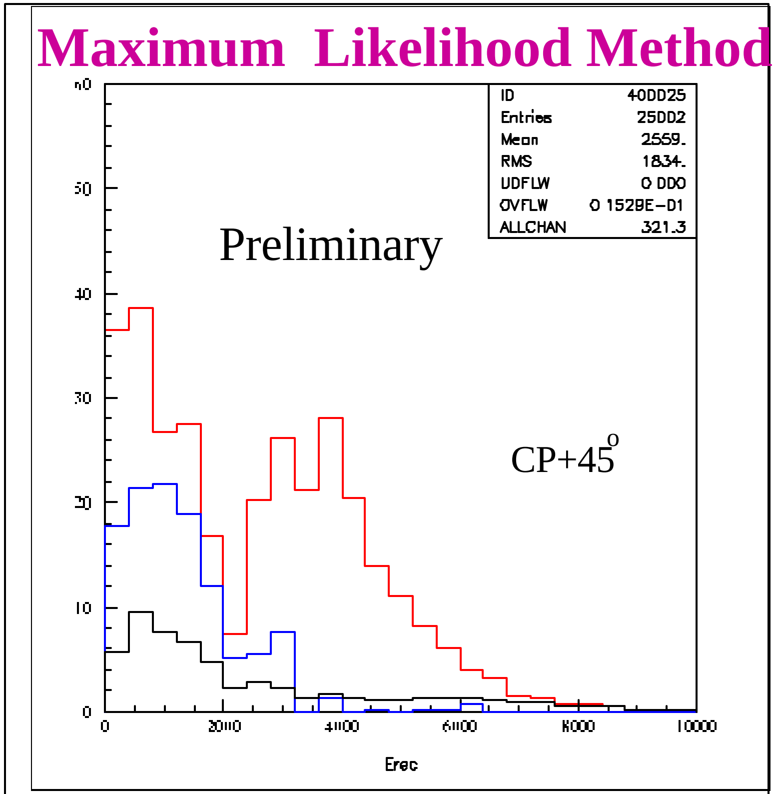
- Effect of cut on Δ likelihood

ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for background

No Δlikelihood cut (100% signal retained)

Δlikelihood cut (~50% signal retained)





E_{rec}

Signal 700 ev Bkgs 2005
(1878 from π^0+others)
(127 from ν_e)

E_{rec}

Signal 321 ev Bkgs 169
(112 from π^0+others)
(57 from ν_e)

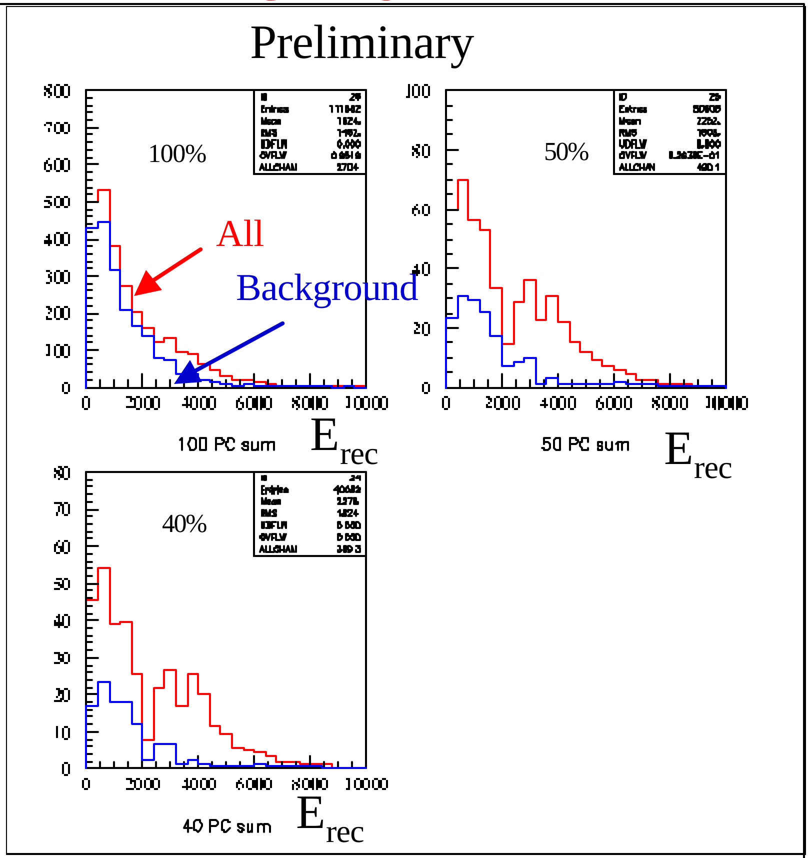
Maximum Likelihood Method

S/B

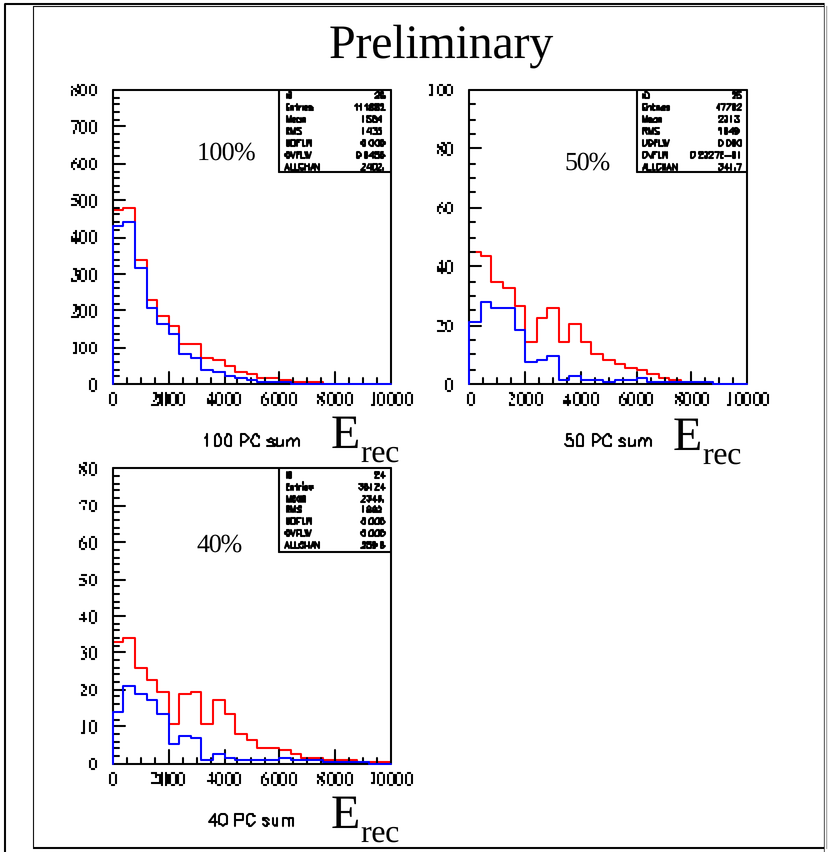
ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

- Effect of cut on likelihood

CP +45^o



CP-45^o



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Maximum Likelihood Method

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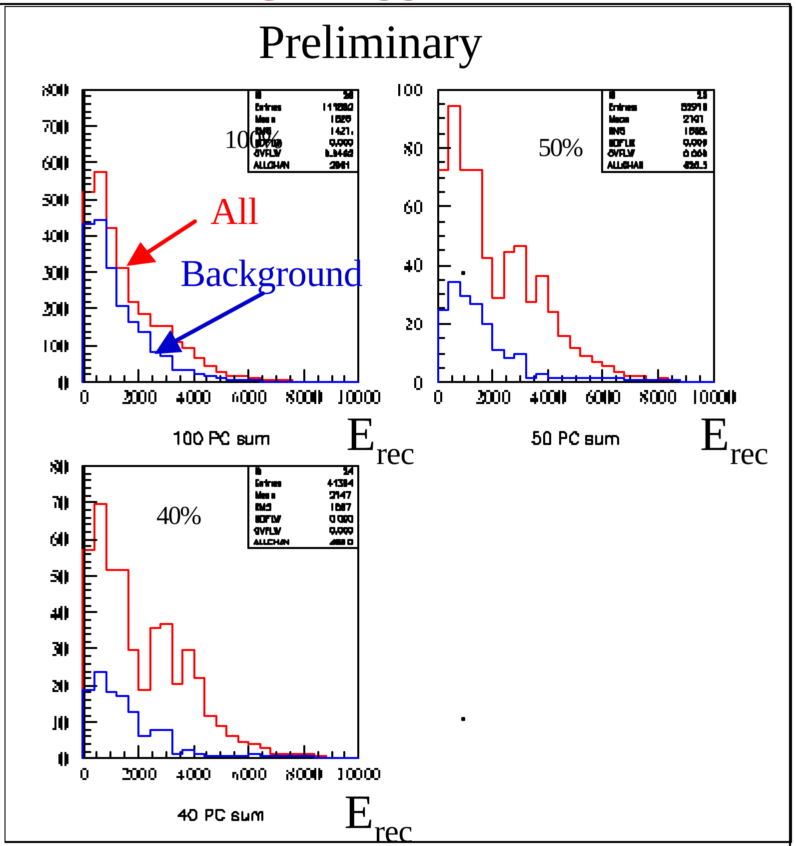
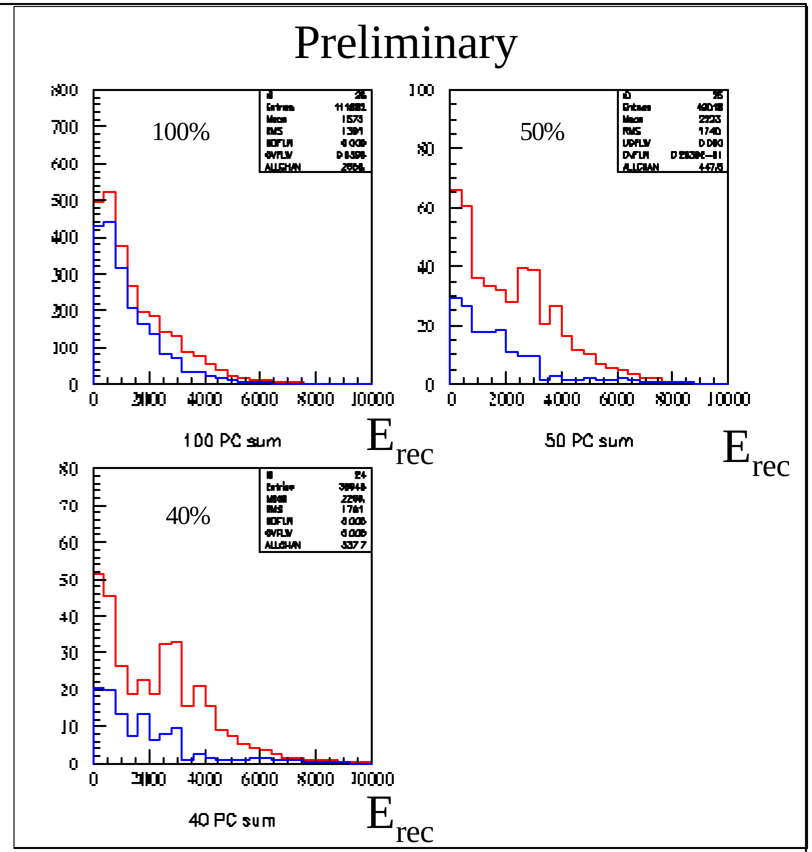
CP +135°



CP-135°



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Comparison of Future Neutrino Oscillations Exps.

Parameter	T2K	T2K2	Reactor	NOνA	NOνA2	VLBNO.
Δm_{32}^2	± 4 %	± 4 %	-	± 2 %	± 2 %	± 1 %
$\sin^2(2\theta_{23})$	±1.5 %	± 0.4 %	-	± 0.4 %	± 0.2 %	± 0.5 %
$\sin^2(2\theta_{13})$ [a]	>0.02	>0.01	>0.01	>0.01	>0.01	>0.01
$\Delta m_{21}^2 \sin(2\theta_{12})$ [b]	-	-	-	-	-	12 %
sign of (Δm_{32}^2) [c]	-	-	-	possible	yes	yes
measure δ_{CP} [d]	-	~20°	-	-	~20°	±13°
N-decay gain	x1	x20	-	-	-	x8
Detector (Ktons)	50	1000	20	30	30+50	400
Beam Power (MW)	0.74	4.0	14000	0.4	2.0	1.5
Baseline (km)	295 [e]	295 [e]	1	810 [e]	810 [e]	>2500
Detector Cost (\$M)	exists	~1000	~20	165	+200	400
Beam Cost (\$M)	exists	500	exists	50	1000	400
Ops. Cost (\$M/10 yrs)	500	700	50	500	600	150/500 [f]

Both results needed to resolve ambiguities!

Best Bets

[a] detection of $\nu_\mu \rightarrow \nu_e$, upper limit on or determination of $\sin^2(2\theta_{13})$
[b] detection of $\nu_\mu \rightarrow \nu_e$ appearance, even if $\sin^2(2\theta_{13}) = 0$; determine θ_{23} angle ambiguity
[c] detection of the matter enhancement effect over the entire δ_{CP} angle range
[d] measure the CP-violation phase δ_{CP} in the lepton sector; NOνA2 depends on T2K2
[e] beam is 'off-axis' from 0-degree target direction; [f] with/without RHIC operations

Conclusions

- Neutrino Oscillations parameters can be completely determined within the next two decades
- The most effective method is the VLBNO + Wideband Super Beam
- A Megaton-class Water Cerenkov Detector can do this experiment
- The AGS-based Super Neutrino Beam is the best neutrino source
- Combining VLBNO with the Nucleon Decay search in the NSF DUSEL is the most science and cost effective plan for the U.S.

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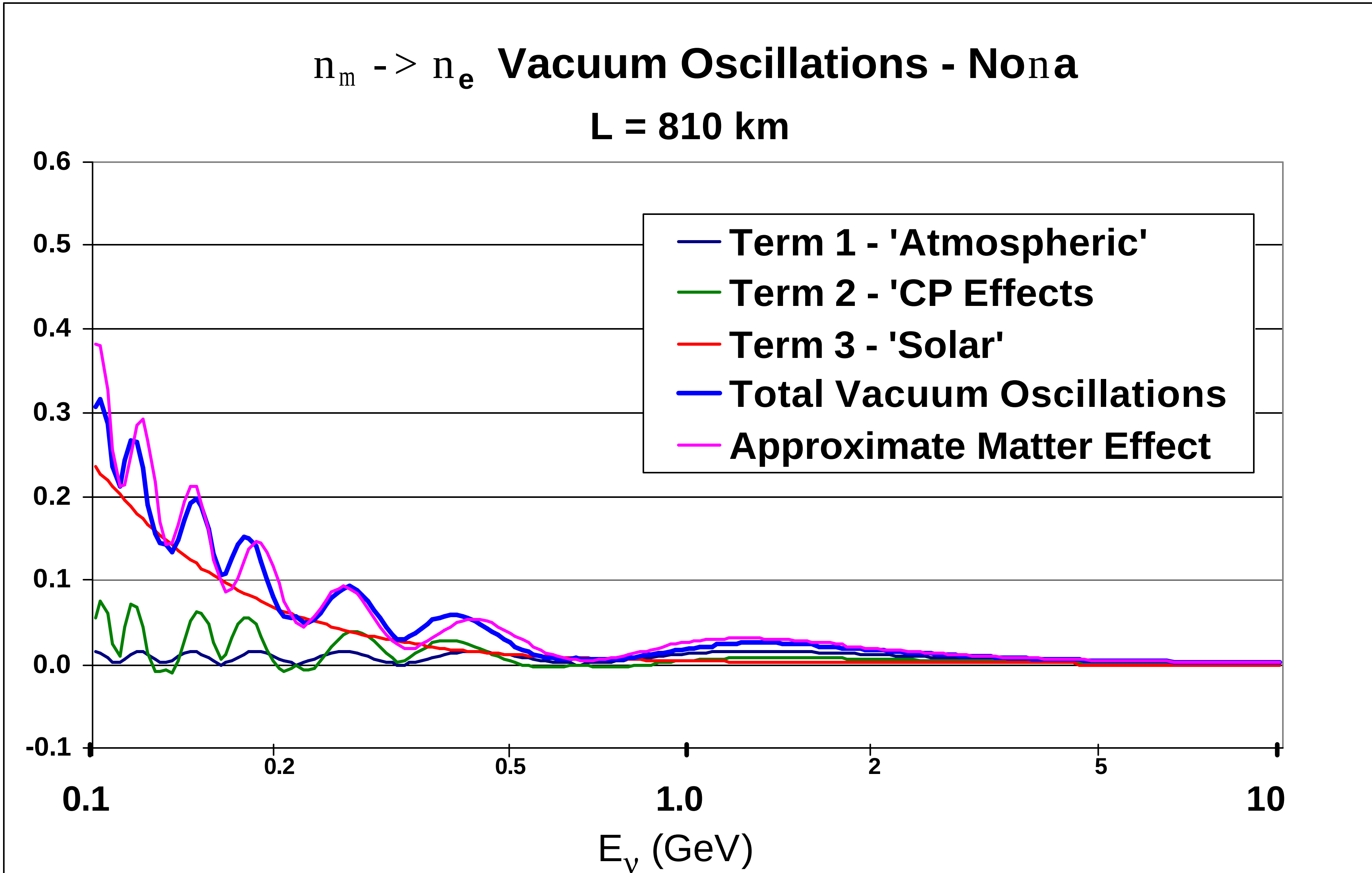

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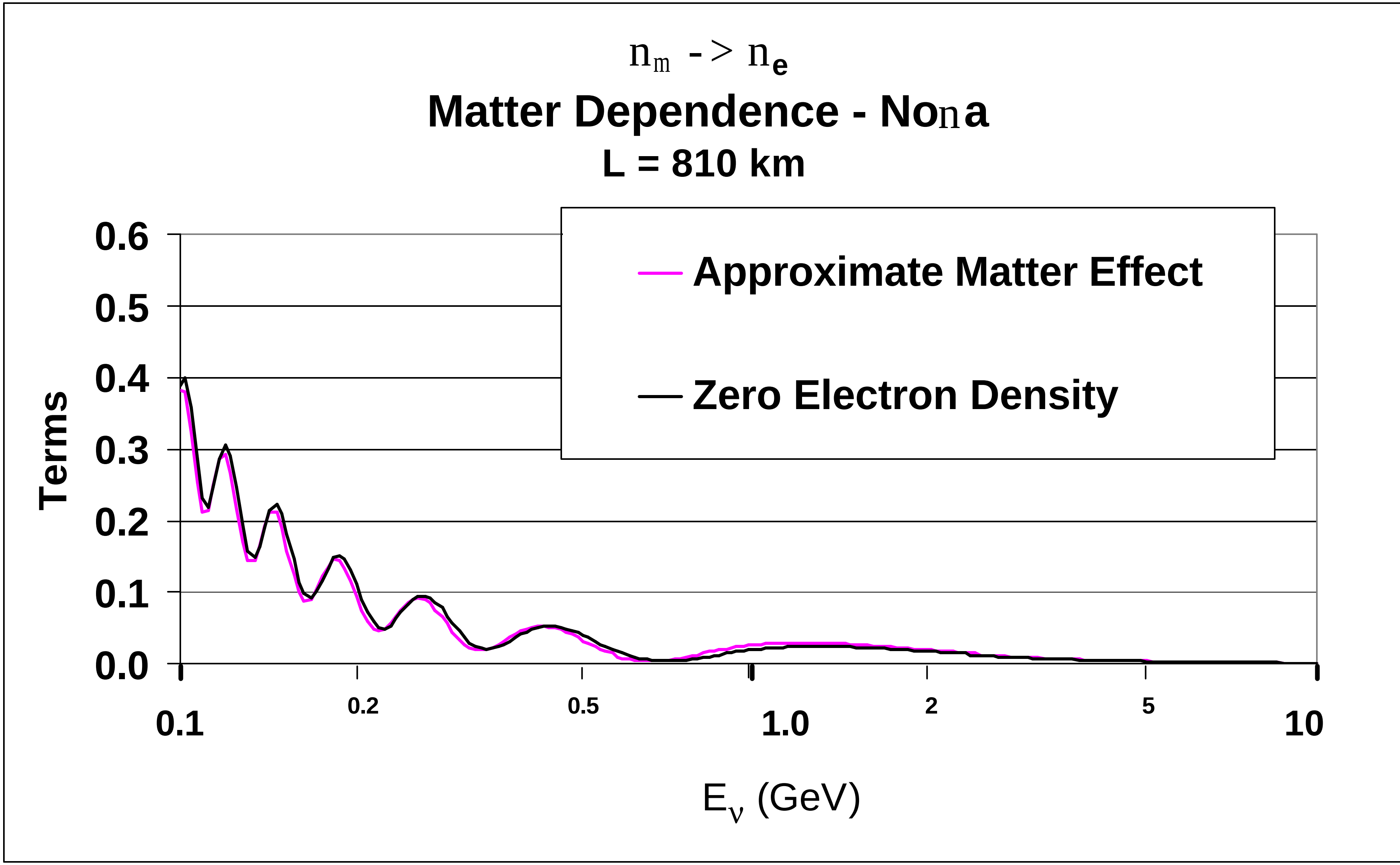

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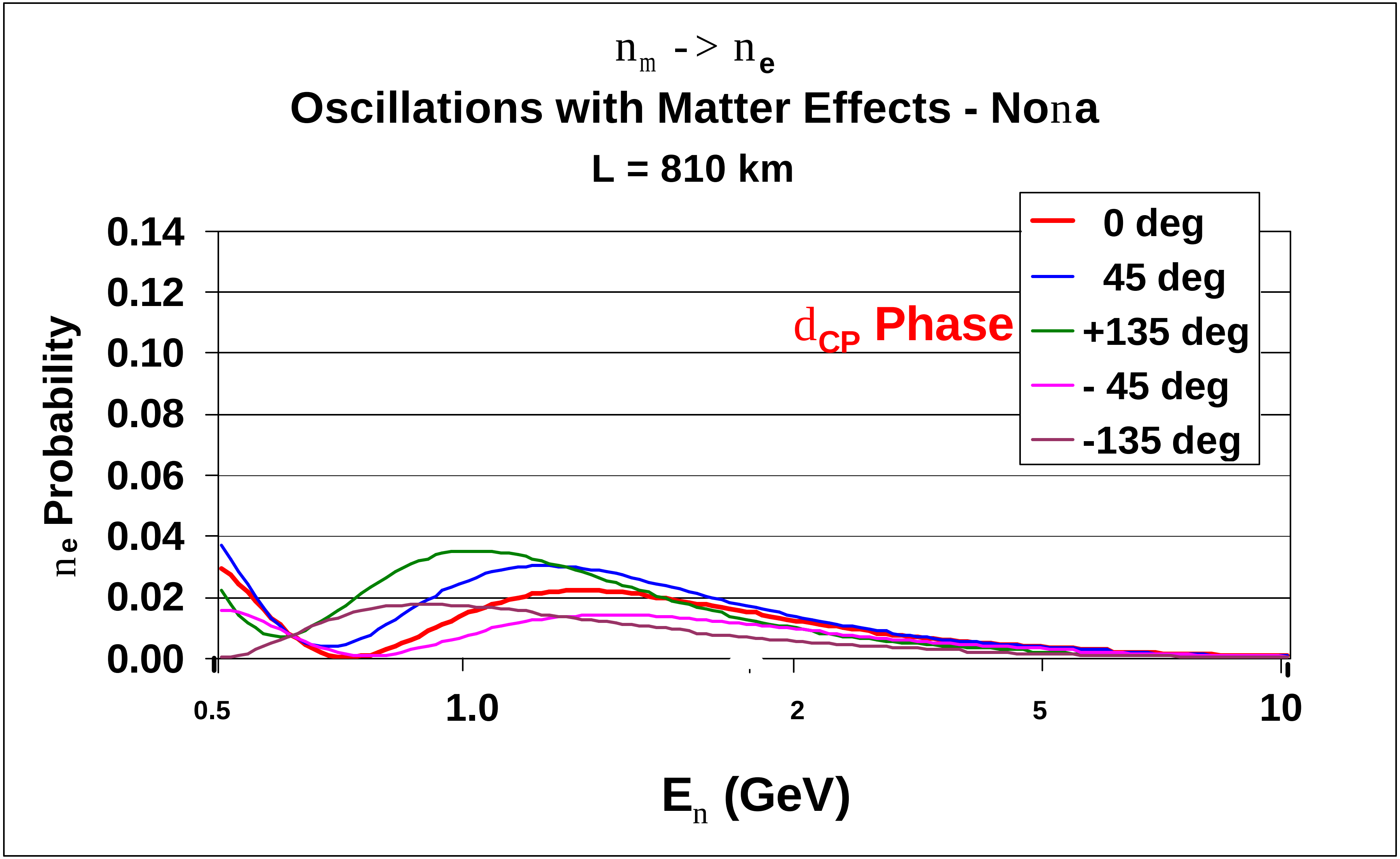

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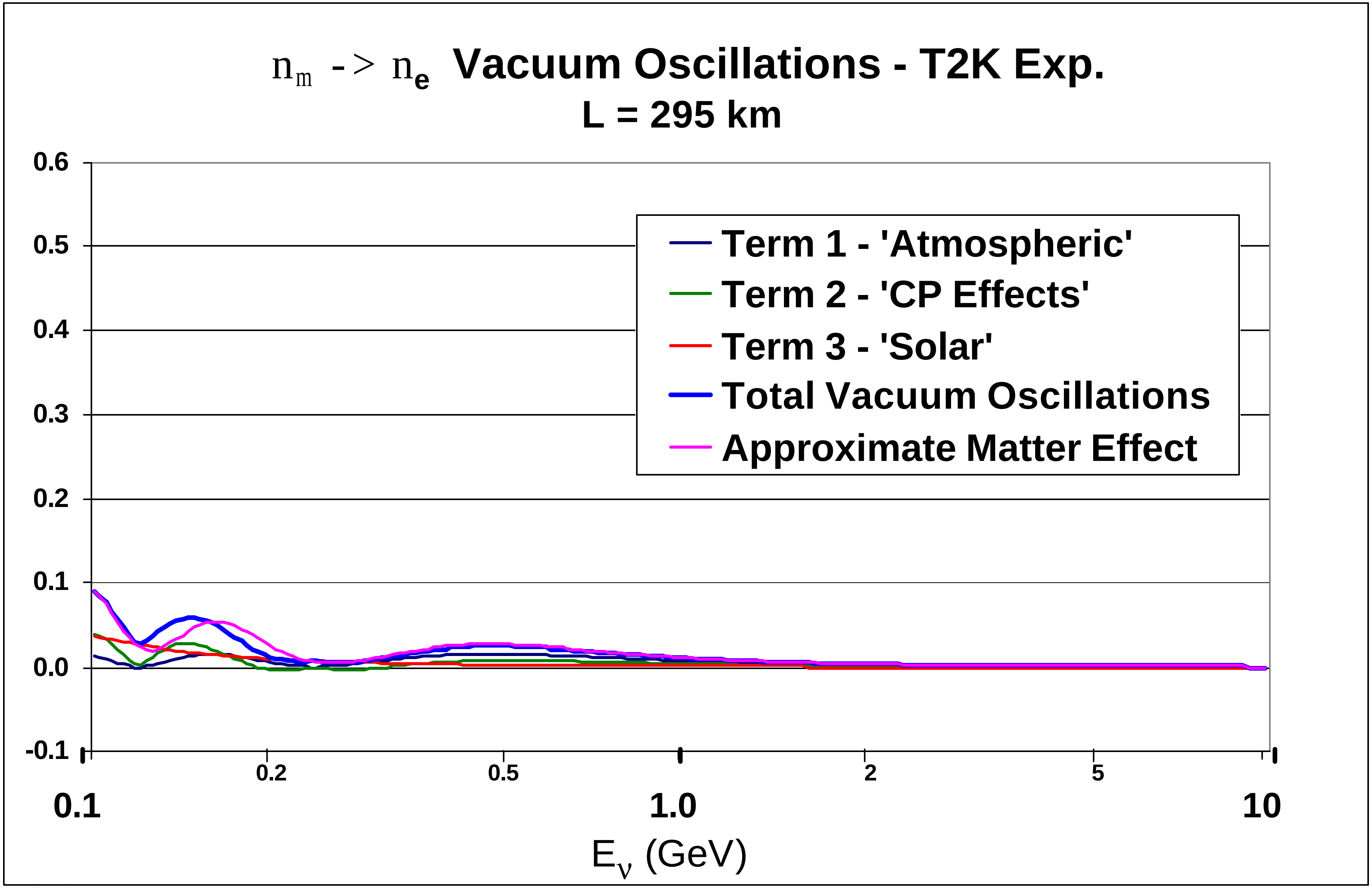

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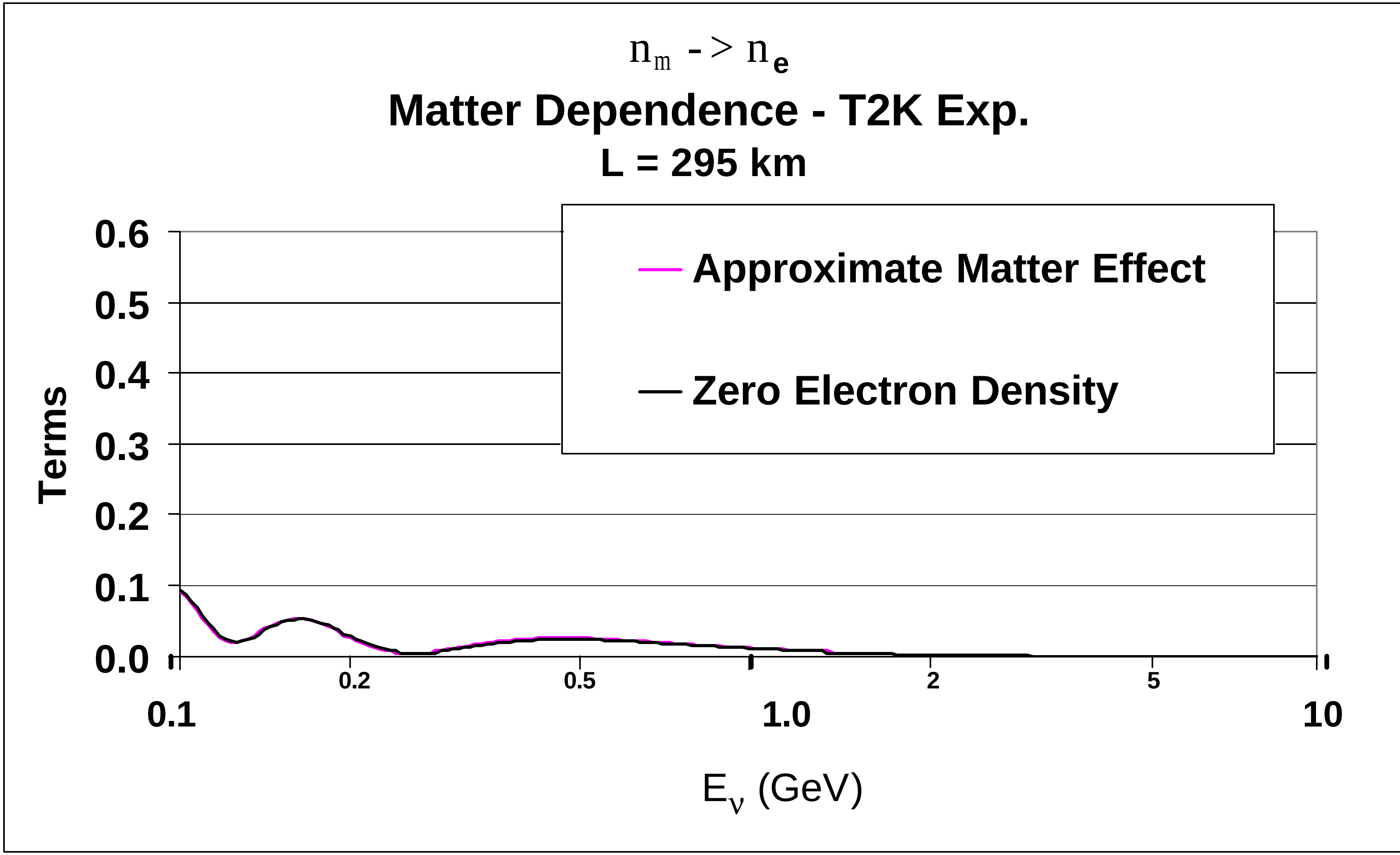

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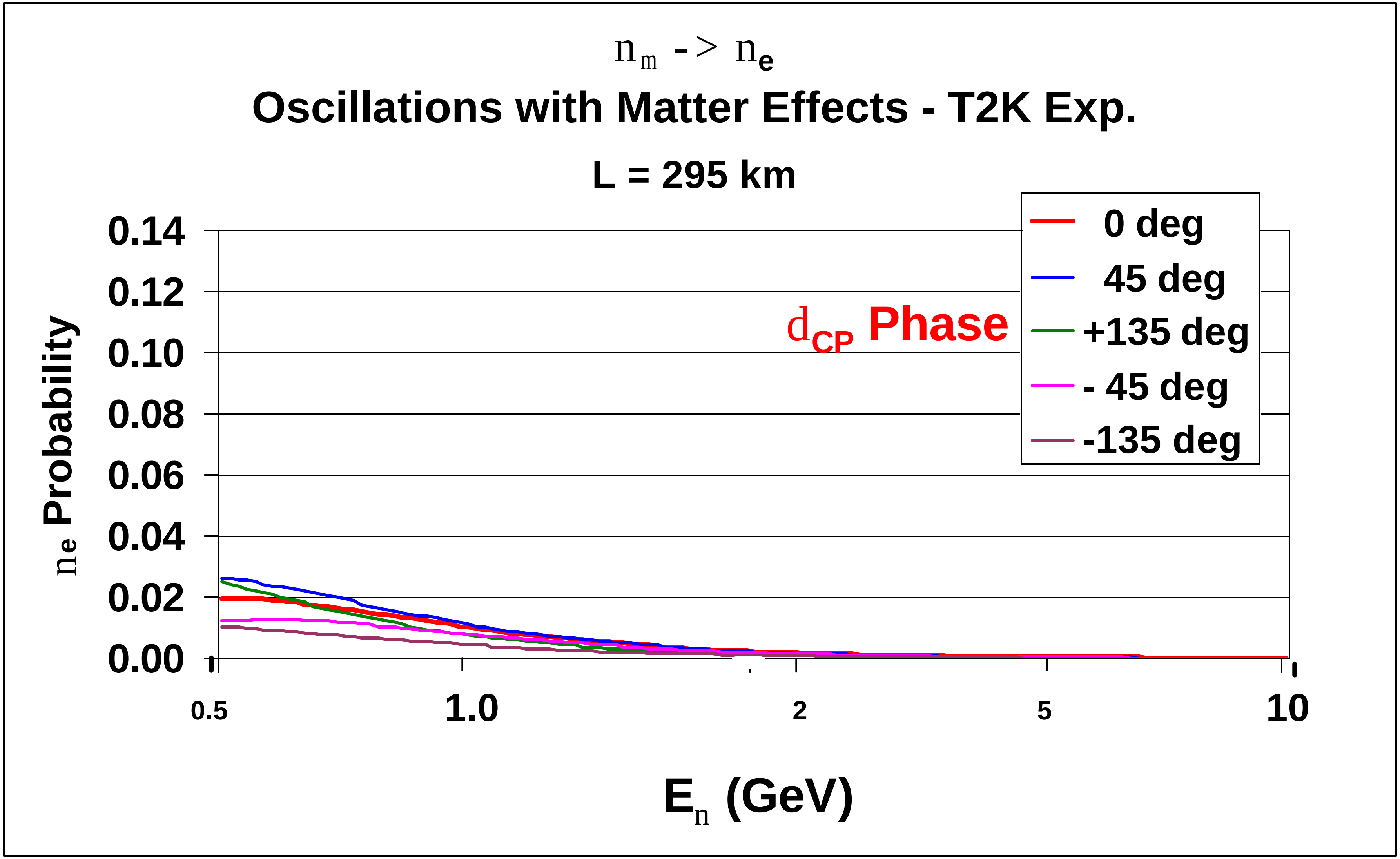

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